

Solar charge-consumption parity in multirotor UAVs: a reproducible simulation study

Sajid Kabir Saji

Independent researcher, Dhaka, Bangladesh

ORCID: 0009-0008-1393-6111

Contact: sajidkabirsaji@gmail.com

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Abstract

Solar power has enabled multi-day continuous flight in fixed-wing unmanned aerial vehicles (UAVs), and it is natural to ask whether the same approach can free multirotor UAVs from their short endurance. This paper tests that question with an open, reproducible energy-balance simulation. A 24-hour model couples a clear-sky solar resource model, a photovoltaic panel model, momentum-theory hover power for a quadcopter, and a battery with charge and discharge losses. For a reference vehicle (3 kg quadcopter, 1 m² of panel at 22 percent efficiency, 500 Wh battery) flying continuously at 100 m over Dhaka on the summer solstice, the model harvests 1567.3 Wh against a flight demand of 6612.8 Wh, a net deficit of 5045.5 Wh per day. A parity solver shows the solar input would have to be multiplied by 4.22 to break even, equivalent to about 4.2 m² of panel on a 3 kg quadcopter, or a physically impossible 93 percent panel efficiency at 1 m². Sensitivity analysis shows the deficit is structural: battery size does not change the daily balance at all, halving vehicle mass still leaves a deficit, and no latitude or season closes the gap. The conclusion is that charge-consumption parity is not reachable for small solar multirotors with current photovoltaic and battery technology, and that the realistic role of solar on multirotors is partial endurance extension, while the larger near-term gains lie in autonomous energy management. All code, parameters, and figures are released under an open license with a citable DOI so that every number in this paper can be regenerated.

Keywords: solar UAV; multirotor; energy balance; endurance; reproducibility; photovoltaic

1. Introduction

Endurance is the binding constraint on multirotor unmanned aerial vehicles. A typical small quadcopter flies for 20 to 40 minutes on a battery charge, which limits its use in inspection, mapping, delivery, and public-safety missions. Fixed-wing solar aircraft have taken the opposite path: by covering a large, efficient wing with photovoltaic cells and flying slowly, aircraft such as AtlantikSolar have flown continuously for more than 80 hours [1]. These successes invite a simple question: can a multirotor do the same?

The intuition that it cannot rests on two facts. A multirotor stays airborne by accelerating air downward with small rotors, which is an energetically expensive way to fly; and its airframe offers little flat area for solar cells compared with a wing. But intuition is not a measurement. Designers, students, and startups still announce solar quadcopter concepts, and the author's own undergraduate thesis project in 2022 was a solar-powered quadcopter [2]. What the field needs for this class of vehicle is not another optimistic concept but a quantified, checkable answer: how large is the gap between what the sun delivers to a multirotor and what hovering consumes, and how does that gap move with the design parameters?

This paper provides that answer with an intentionally simple model whose every assumption is visible in open-source code. The contribution is threefold:

1. A reproducible 24-hour energy-balance simulation of a solar multirotor, released as versioned, citable software [3].
2. A quantified parity analysis: a single parity factor stating how many times the available solar input must be multiplied for daily harvest to equal daily demand.

3. A sensitivity map over panel area, cell efficiency, vehicle mass, battery size, latitude, season, and altitude, showing which parameters matter and which do not.

The headline result is negative, and it is reported as such: for the reference vehicle the daily deficit is 5045.5 Wh, about 3.2 times the entire harvest. Negative results of this kind are useful precisely because they are checkable; anyone who disagrees with a parameter can change it and re-run the study in minutes.

2. Background and related work

Solar flight is a solved problem for one configuration and an open one for another. For fixed-wing aircraft, Noth's design methodology for continuous solar flight [4] and the AtlantikSolar programme [1] established the energy-balance method used here: model the solar resource over a full day, model consumption, size the battery for the night, and require the daily balance to close with margin. AtlantikSolar, a 6.93 kg hand-launched fixed-wing aircraft, flew 81 hours continuously in July 2015, with a minimum battery state of charge of 39 percent in summer at mid-European latitudes [1]. High-altitude fixed-wing aircraft such as Zephyr have extended this to weeks. In every successful case the configuration is a large, lightly loaded wing: low consumption per unit area, and a large area to harvest with.

Multirotors invert both terms. Hover power for a rotorcraft follows momentum theory and grows with the $3/2$ power of weight, while the disc area of small rotors is tiny compared with a wing of the same span. A 3 kg quadcopter needs on the order of 275 W simply to hover, continuously, day and night. Against this, a square metre of good photovoltaic panel delivers at most about 200 to 220 W at solar noon under a clear sky, and far less averaged over a day. The question is therefore not whether a solar multirotor can harvest something, it plainly can, but whether the daily integrals can ever meet.

Published multirotor solar work is mostly at the level of prototypes that extend flight time by minutes or demonstrate charging on the ground, rather than closing the daily balance in flight. To the author's knowledge, no reproducible, open quantification of the parity gap for a reference multirotor has been published. This paper fills that gap with a deliberately transparent model.

3. Model and methods

3.1 Solar resource

The model computes clear-sky irradiance on a horizontal surface from latitude, day of year, and hour of day, using standard solar geometry (declination, hour angle, solar altitude) of the kind set out in Duffie and Beckman [5], with a clear-sky attenuation of the extraterrestrial irradiance. Clouds, aerosols beyond the clear-sky assumption, and weather are excluded; the model therefore describes a best-case day, which is the right basis for a feasibility claim: if parity fails on a clear day, it fails in general.

3.2 Photovoltaic panel

Panel power is $P = G \times A \times \eta$, where G is irradiance in W/m², A is panel area in m², and η is cell efficiency. The reference efficiency of 0.22 reflects good commercial silicon cells. The panel is assumed horizontal and fixed to the airframe, with no tracking and no incidence-angle losses, again a best-case simplification in the panel's favour.

3.3 Propulsion

Hover power is computed from momentum theory [6] for the total rotor disc area, using air density from the International Standard Atmosphere troposphere model [7] at the flight altitude. The reference vehicle is a 3 kg quadcopter with four 0.33 m propellers. Forward flight, climb, wind, and manoeuvre loads are excluded; hover is the minimum-power state for a multirotor at zero airspeed in still air, so the consumption side is also best-case.

3.4 Battery

The battery is modelled with capacity, charge efficiency (0.95), discharge efficiency (0.97), and a maximum depth of discharge of 0.8. The reference capacity is 500 Wh. The battery starts the simulated day full.

3.5 Simulation and the parity criterion

The simulation steps through 24 hours at 5-minute resolution. At each step it computes harvested power and hover load; surplus charges the battery, deficit discharges it. Two quantities define the outcome:

- **Daily energy balance:** total harvested energy minus total flight energy over 24 hours of continuous flight. Parity means a balance of zero or better.
- **Parity factor:** the multiplier on the solar input (equivalently, on panel area or efficiency) at which the balance crosses zero, found by bisection. A factor of 1.0 means parity as configured; 4.22 means the solar input must be 4.22 times larger.

One modelling choice deserves emphasis: the flight load is applied for the full 24 hours, including the night. This is the correct test for the claim usually made for solar aircraft, continuous flight. Section 6 discusses duty-cycled operation, where the vehicle lands or perches at night, as a separate and easier problem.

3.6 Reference configuration

Parameter	Value
Location	Dhaka, Bangladesh (23.8 deg N)
Day of year	172 (summer solstice)
Flight altitude	100 m
Vehicle	Quadcopter, 3.0 kg, 4 rotors of 0.33 m
Panel	1.0 m ² , efficiency 0.22
Battery	500 Wh, 80 percent max depth of discharge

4. Results

4.1 Reference case

On the reference day the sun is above the horizon for 13.47 hours and clear-sky irradiance peaks at 952.7 W/m² at noon (Figure 1). The 1 m² panel at 22 percent efficiency converts this to a peak electrical output of 203.3 W. Hover power at 100 m, where air density is 1.2133 kg/m³, is 274.6 W. The peak solar output therefore never reaches the hover load even at noon on the best day of the year: at every minute of the day the vehicle is a net energy consumer.

Over 24 hours the panel harvests 1567.3 Wh and continuous hover consumes 6612.8 Wh, a net balance of -5045.5 Wh. The harvest covers 23.7 percent of demand. Starting full at midnight, the battery reaches its depth-of-discharge floor at hour 1.33, before sunrise, and never recovers above the floor because solar power never exceeds the load. Under continuous flight the reference vehicle cannot survive its first night, let alone reach daily parity.

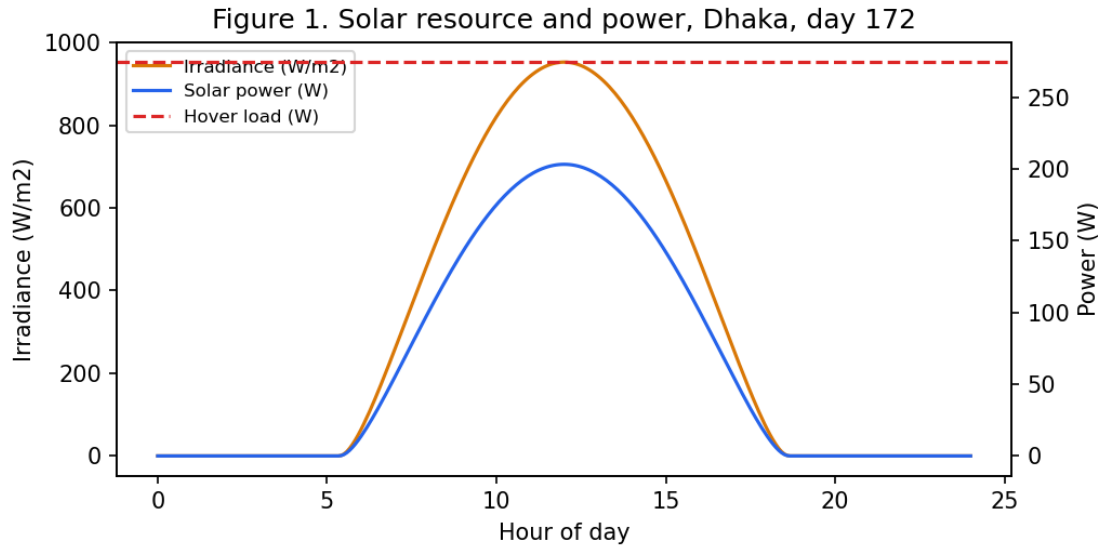


Figure 1: Irradiance, panel power, and hover load across the reference day. The load line sits above the solar curve at all hours.

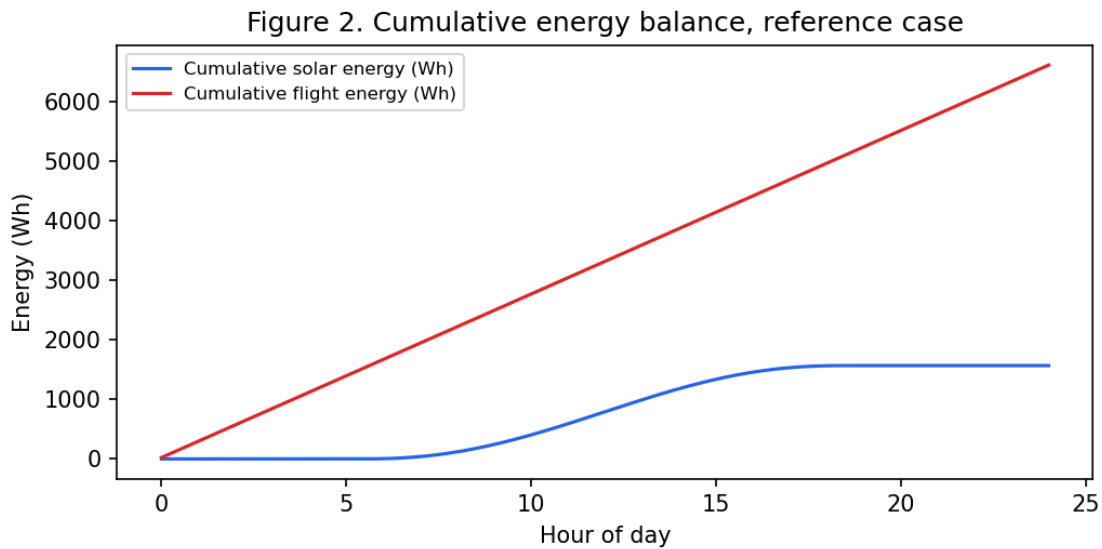


Figure 2: Cumulative harvested and consumed energy. The gap widens through the night, narrows slightly in growth rate at midday, and never closes.

4.2 The parity requirement

The parity factor for the reference configuration is 4.22. Read three ways, it is the same wall:

- The solar resource would have to be 4.22 times stronger than a clear solstice day in Dhaka.
- The panel would have to cover about 4.2 m², on a 3 kg quadcopter whose own footprint is a fraction of a square metre.
- At 1 m², cell efficiency would have to reach about 93 percent, beyond the theoretical limit of any single-junction or practical multi-junction cell at this scale.

Figure 3 shows the crossing directly: net daily energy reaches zero only between 4 and 6 m² of panel, at 4.22 m² by interpolation of the solver result.

Panel area (m ²)	Harvest (Wh)	Net (Wh)
0.25	391.8	-6220.9
0.5	783.6	-5829.1

1.0	1567.3	-5045.5
1.5	2350.9	-4261.9
2.0	3134.5	-3478.2
3.0	4701.8	-1910.9
4.0	6269.1	-343.7
6.0	9403.6	+2790.9
8.0	12538.2	+5925.4

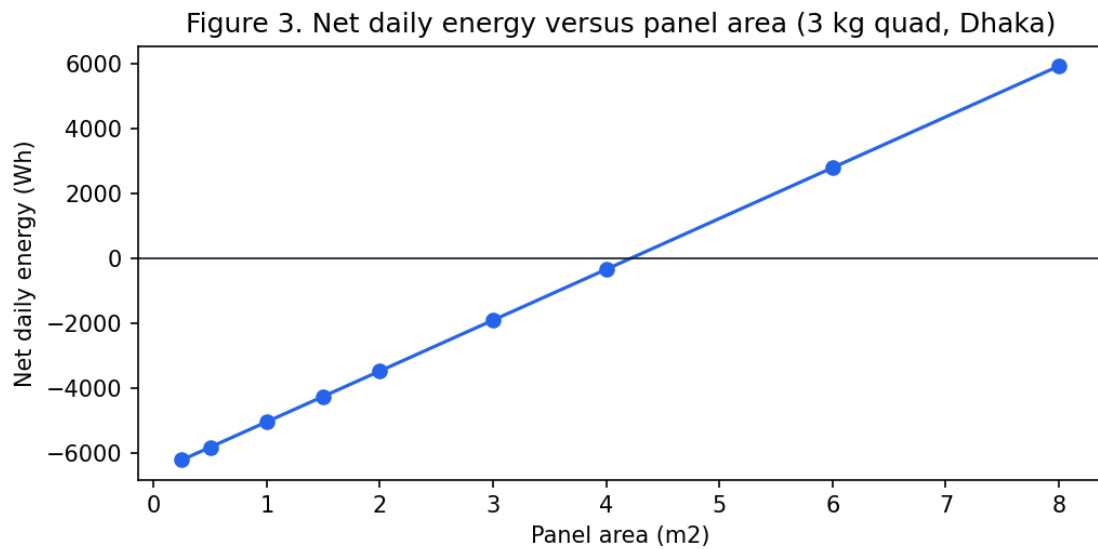


Figure 3: Net daily energy against panel area. Parity needs a wing-sized collector on a rotorcraft frame.

4.3 Sensitivity analysis

Cell efficiency. Better cells help linearly and insufficiently. At 1 m2, raising efficiency from 0.15 to 0.40 moves the balance from -5544.2 Wh to -3763.2 Wh, and the parity factor only falls from 6.19 to 2.32. Even a hypothetical 40 percent cell leaves the vehicle needing more than twice its panel area again.

Vehicle mass. Consumption grows steeply with mass (Figure 4). Hover power is 100.3 W at 1.5 kg, 151.7 W at 2 kg, 274.6 W at 3 kg, 585.0 W at 5 kg, and 1178.9 W at 8 kg. A 1.5 kg vehicle with the same 1 m2 panel still ends the day at -848.5 Wh. Lightening the vehicle narrows the gap faster than any other single change, but a panel of 1 m2 on a 1.5 kg quadcopter is already an extreme configuration, and parity is still not reached.

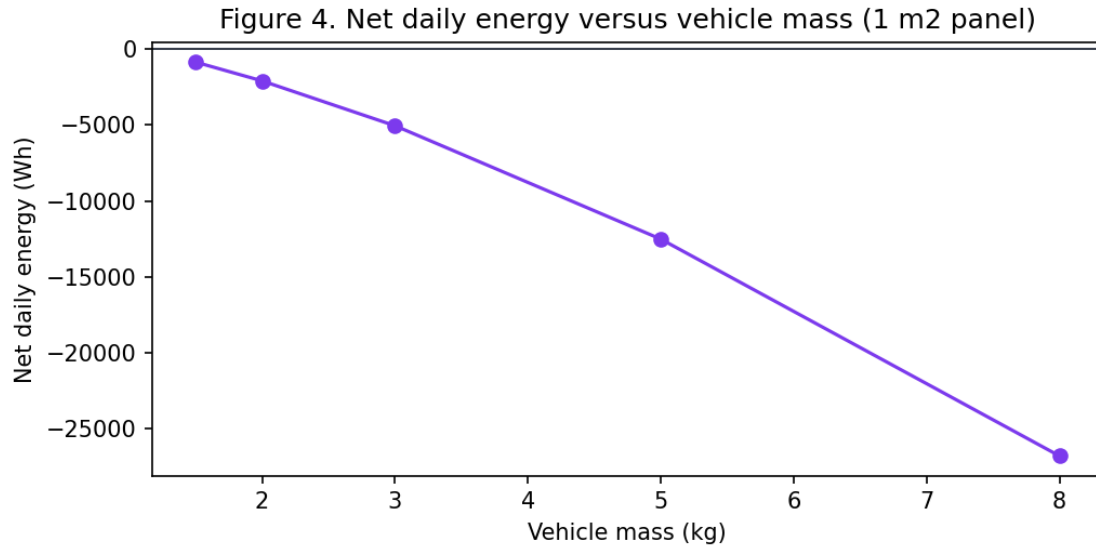


Figure 4: Net daily energy against vehicle mass at fixed 1 m² panel.

Battery size. Battery capacity has no effect on the daily balance whatsoever: 250, 500, 1000, and 2000 Wh batteries all produce the identical net of -5045.5 Wh, differing only in the depth-of-discharge floor (50, 100, 200, and 400 Wh of unusable reserve respectively). Storage shifts energy in time; it does not create it. Any design study that proposes to reach parity by enlarging the battery is answering the wrong question.

Latitude and season. Geography moves the harvest, never enough. On the summer solstice, London (51.5 deg N) harvests 1552.7 Wh, nearly matching Dhaka's 1567.3 Wh, because its 16.4-hour day compensates for a lower sun. Winter reverses the picture: Dhaka falls to 753.2 Wh and London to 128.8 Wh. The equator on day 172 yields 1268.6 Wh. In every case the balance stays near -5000 Wh or worse.

Altitude. Between sea level and 2000 m, hover power rises from 273.3 W to 301.0 W as the air thins, worsening the balance from -5014.4 Wh to -5681.3 Wh. Altitude is a minor term at multirotor operating heights.

5. Discussion

The deficit is structural, not a matter of tuning. It comes from the ratio of two areas: the rotor disc area that sets hover power through momentum theory, and the collector area the airframe can present to the sun. A fixed-wing aircraft couples these favourably, since the wing is both the lifting surface and the collector, and it lifts at a fraction of hover power. A multirotor's lifting surface is its rotor discs, which cannot carry cells, and its body area is small. The parity factor of 4.22 is that geometric mismatch expressed as an energy number.

Three implications follow. First, claims of solar multirotors in continuous flight should be met with one question: what is the parity factor, computed over 24 hours? Any claim that does not close the full-day balance is describing partial assistance, not solar flight. Second, solar on a multirotor is not useless; it is mis-sold. A panel that covers 24 percent of hover demand on a good day can extend daytime endurance meaningfully, offset avionics and payload power entirely, and recharge the vehicle between sorties. Those are real engineering benefits, and they are the honest scope for solar on rotorcraft. Third, the binding constraint is demand, not supply: since storage cannot create energy and collectors cannot grow on this airframe, the largest remaining lever is reducing the energy cost of staying aloft and of the mission itself, through lighter structures, larger slower rotors, and above all autonomous energy management that decides when to fly, when to perch, and how to spend a finite energy budget. That is where the author's current research is directed, with solar as a complement rather than the main actor.

6. Limitations

This study is deliberately simple, and its simplifications should be kept in view. The sky is clear every day; real weather only worsens the harvest, so the feasibility conclusion is conservative. The panel is horizontal with no incidence-angle or temperature losses, and the load is pure hover in still air with no wind, climb, or payload power; all of these favour the solar case, so the true gap is larger than reported. The model is a simulation, not flight measurement; its propulsion term is ideal momentum theory with the losses folded into constant efficiencies, and it has not been validated against a physical solar quadcopter. The continuous-flight criterion is the strictest reading of parity: a vehicle that lands at night and recharges by day faces a different, easier balance, which the same code can evaluate by changing the load profile, and which is a planned extension. None of these limitations plausibly reverses the conclusion, because most act to widen the gap, and the gap is a factor of four.

7. Reproducibility

Every number in this paper was produced by solar-uav-sim, released under the MIT license. Version 1.0.1 is archived on Zenodo (DOI: 10.5281/zenodo.23077718; concept DOI: 10.5281/zenodo.23077717) and developed openly on GitHub. The reference case is the project's documented example; the sensitivity sweeps are single-parameter variations of it through the public API. The figures are generated by the same code from the same parameters. A reader with Python can regenerate the reference result with the example script in minutes and check each table entry against the functions described in Section 3.

8. Conclusions

For a representative small quadcopter, solar charge-consumption parity in continuous flight is out of reach by a factor of about 4.2 in solar input. The gap persists across panel efficiencies up to 40 percent, vehicle masses down to 1.5 kg, all tested latitudes and seasons, and any battery size. Solar power remains valuable on multirotors as an endurance extender and a between-sortie charger, but the path to step-change multirotor endurance lies in reducing and intelligently managing energy demand, not in harvesting more of it. Publishing this negative result with fully open code is intended to save other designers the cost of rediscovering the wall, and to give future claims a benchmark they must meet.

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Author note

The author is an aeronautical engineering graduate (BEng, Nanchang Hangkong University, 2022) working as an independent researcher. The 2022 thesis project in reference [2] was a solar-powered quadcopter; this study is, in part, its author checking his own undergraduate assumptions with better tools and reporting what he found. No funding supported this work. The author declares no competing interests.